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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification ⁶ : G02B 26/02	A2	(11) International Publication Number: WO 99/52006 (43) International Publication Date: 14 October 1999 (14.10.99)
(21) International Application Number: PCT/US99/07271 (22) International Filing Date: 1 April 1999 (01.04.99) (30) Priority Data: 09/056,975 8 April 1998 (08.04.98) US (63) Related by Continuation (CON) or Continuation-in-Part (CIP) to Earlier Application US 09/056,975 (CON) Filed on 8 April 1998 (08.04.98) (71) Applicant (for all designated States except US): ETALON, INC. [US/US]; Suite 501, 354 Congress Street, Boston, MA 02110-1237 (US). (72) Inventor; and (75) Inventor/Applicant (for US only): MILES, Mark, W. [US/US]; Suite 501, 354 Congress Street, Boston, MA 02110-1237 (US). (74) Agent: FEIGENBAUM, David, L.; Fish & Richardson P.C., 225 Franklin Street, Boston, MA 02110-2804 (US).		(81) Designated States: KR, US. Published <i>Without international search report and to be republished upon receipt of that report.</i>
(54) Title: INTERFEROMETRIC MODULATION OF RADIATION (57) Abstract <p>The invention features an interferometric modulator comprising a cavity defined by two walls. At least two arms connect the two walls to permit motion of the walls relative to each other. The two arms are configured and attached to a first one of the walls in a manner that enables mechanical stress in the first wall to be relieved by motion of the first wall essentially within the plane of the first wall.</p> <div data-bbox="909 1134 1364 1575"><p>The diagram illustrates a mechanical structure for an interferometric modulator. It consists of a central square cavity, labeled 100, which contains a circular feature. Two arms, labeled 102 and 104, are attached to the walls of the cavity. Arm 102 is on the left side, and arm 104 is on the top side. An arrow points upwards from the right side of the cavity, indicating a direction of motion or force.</p></div>		

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INTERFEROMETRIC MODULATION OF RADIATION
Cross Reference To Related Applications

5 This is a continuation in part of United States Patent Applications Serial Numbers 08/238,750, 08/554,630, and 08/769,947 filed May 5, 1994, November 6, 1995, and December 19, 1996 respectively, and incorporated by reference.

10 Background

 This invention relates to interferometric modulation.

 Interference modulators (IMods) are a broad class of devices that modulate incident light by the manipulation of admittance via the modification of the device's interferometric characteristics. Applications for such devices include displays, optical processing, and optical information storage.

Summary

20 In general, in one aspect, the invention features an interferometric modulator comprising a cavity defined by two walls. At least two arms connect the two walls to permit motion of the walls relative to each other. The two arms are configured and attached to a first one of the walls in a manner that enables mechanical stress in the first wall to be relieved by motion of the first wall essentially within the plane of the first wall.

 Implementations of the invention may include one or more of the following features. The motion of the first wall may be rotational. Each of the arms has two ends, one of the ends attached to the first wall and a second end that is attached at a point that is fixed relative to a second one of the walls. The point of attachment of the second end is offset, with reference to an axis that is perpendicular to the first wall, from the end that is attached to the second wall. The first wall

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has two essentially straight edges and one end of each of the arms is attached at the middle of one of the edges or at the end of one of the edges. A third arm and a fourth arm also each connects the two walls. The arms define a
5 pinwheel configuration. The lengths, thicknesses and positions of connection to the first wall of the arms may be configured to achieve a desired spring constant.

In general, in another aspect, the invention features an array of interferometric modulators. Each of
10 the interferometric modulators has a cavity defined by two walls and at least two arms connecting the two walls to permit motion of the walls relative to each other. The walls and arms of different ones of the modulators are configured to achieve different spring constants
15 associated with motion of the walls relative to each other.

In general, in another aspect, the invention features a method of fabricating an interferometric modulator, in which two walls of a cavity are formed,
20 connected by at least two arms. After the forming, a first one of the walls is permitted to move in the plane of the first wall relative to the arms to relieve mechanical stress in the first wall.

In general, in another aspect, the invention
25 features an interferometric modulator comprising three walls that are generally parallel to one another. The walls are supported for movement of at least one of the walls relative to the other two. Control circuitry drives at least one of the walls to discrete positions
30 representing three discrete states of operation of the modulator.

Implementations of the invention may include one or more of the following features. In one of the three discrete states, there is a gap between the first and a
35 second of the two walls and a gap between the second and

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a third of the two walls. In a second of the three discrete states, there is a gap between the first and the second of the two walls and no gap between the second and the third of the two walls. In the third of the three
5 discrete states, there is no gap between the first and the second of the two walls and no gap between the second and the third of the two walls. Each membrane includes a combination of dielectric, metallic, or semiconducting films.

10 In general, in another aspect, an interference modulator includes a cavity defined by two walls that are movable relative to one another to and from a contact position in which the two walls are essentially adjacent to one another. Spacers are mounted to form part of one
15 of the walls to reduce the surface area over which the two walls touch in the contact position.

Implementations of the invention may include one or more of the following features. The spacers comprise electrodes and conductors feed current to the electrodes.

20 In general, in another aspect, the invention features an interference modulator comprising a cavity defined by two walls that are separated by a fluid-filled gap. The walls are movable relative to each other to change the volume of the gap. An aperture (e.g., a round
25 hole in the center) in one of the walls is configured to control the damping effect of fluid moving into or out of the gap as the volume of the gap changes. In implementations of the invention, the aperture comprises a round hole in the center of the wall.

30 In general, in another aspect, the invention features an interference modulator comprising at least two walls that are movable relative to each other to define a cavity between them. The relative positions of the walls define two modes, one in which the modulator
35 reflects incident light and appears white and another in

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which the modulator absorbs incident light and appears black. In implementations, one of the walls may include a sandwich of a dielectric between metals, and the other of the walls may comprise a dielectric.

5 In general, in another aspect, the invention features an interferometric modulator comprising a cavity defined by two walls with at least two arms connecting the two walls to permit motion of the walls relative to each other. The response time of the modulator is
10 controlled to a predetermined value by a combination of at least two of: the lengths of the arms, the thickness of one of the walls, the thickness of the arms, the presence and dimensions of damping holes, and the ambient gas pressure in the vicinity of the modulator.

15 In general, in another aspect, the invention features an interferometric modulator comprising a cavity defined by two walls, at least two arms connecting the two walls to permit motion of the walls relative to each. The modulator includes a charge deposition mitigating
20 device includes at least one of actuation rails or the application of alternating polarity drive voltages.

In general, in another aspect, the invention features an interferometric modulator having one or more cavities each defined by at least two walls held by a
25 support. At least one of the walls or the support has at least two materials such that the electrical, mechanical, or optical properties of the wall or the support differ at different locations in a cross-section of the wall or the support.

30 Implementations of the invention may include one or more of the following features. At least one of the walls and/or the support has a laminate or a gradient of two or more discrete materials. The substrate upon which the microelectromechanical structure is fabricated is
35 completely or substantially immune to the effects of the

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gas phase etchant. The substrate is chemically isolated from the microelectromechanical structures by virtue of an inert film coating. The two materials exhibit respectively different and complementary electrical, mechanical, or optical properties.

In general, in another aspect, the invention features a method for use in fabricating a microelectromechanical structure, in which a gas phase etchant is used to remove a deposited sacrificial layer.

Implementations of the invention may include one or more of the following features. The MEMS has an interference modulator in which a wall of the modulator is formed on the substrate and a plasma, a liquid, or a gas phase etchant removes the sacrificial layer from between the wall and the substrate. The gas phase etchant includes one of the following: XeF_2 , BrF_3 , ClF_3 , BrF_5 , or IF_5 . The sacrificial layer used includes silicon, molybdenum, and tungsten, tantalum or germanium.

In general, in another aspect, the invention features a method of making arrays of microelectromechanical structures on a production line in which electromechanical structures are micromachined on a surface of a glass or plastic substrate that is at least as large as 8" x 8" or 8" in diameter.

Implementations of the invention may include one or more of the following features. Electronic features are fabricated in conjunction with the MEMS. The microelectromechanical structure has interference modulators. Steps of forming the electronic features are overlapping, and in other cases nonoverlapping, with steps of micromachining the structures.

In general, in another aspect, the invention features a method of making a surface micromachined MEM structure in which the sacrificial layer is patterned and etched in one step, and the insulating layer and primary

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actuation electrode are patterned and etched in a separate step.

In general, in another aspect, the invention features a method of making a surface micromachined MEM
5 structure in which the sacrificial layer, the insulating layer, and the primary actuating electrode are patterned and etched in a single masking step.

In general, in another aspect, the invention features a method of making a MEM structure in which the
10 primary actuating electrode and the secondary actuating electrode are electrically isolated by virtue of underetching the insulating layer

Other advantages and features will become apparent from the following description and from the claims.

15 Description

Fig. 1A is a perspective view of a double clamped IMod. Fig. 1B is a perspective view of an IMod with pinwheel tethers and a damping hole. Fig. 1C is a top view of an IMod with pinwheel tethers and a damping hole.
20 Fig. 1D is a top view of an IMod with straight tethers.

Fig. 2A shows a perspective view of a black and white IMod. Fig. 2B shows a side view of the IMod in two states. Fig. 2C illustrates the thin film structure of the IMod. Fig. 2D shows the spectral reflectance
25 function of the IMod in its two states.

Fig. 3A shows a perspective view of a multi-state IMod. Fig. 3B shows a top view. Fig. 3C shows a side view of the IMod in three states. Fig. 3D illustrates the thin film structure of the IMod. Figs. 3E, 3F, and
30 3G show spectral reflectance functions of a green/white/black IMod, a red/white/black IMod, and a blue/white/black IMod, respectively.

Fig. 4A shows the relationship between the multi-state IMod's states and the drive voltage. Fig. 4B shows
35 the related electromechanical hysteresis curves. Figure

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4C illustrates one part of a drive circuit required to actuate such a device.

Fig. 5A shows an IMod, illustrating the effects of charge injection, in the undriven state. Fig. 5B shows
5 the IMod driven. Fig. 5C shows the IMod undriven after charge transfer. Fig. 5D shows the IMod with reverse polarity applied. Fig. 5E shows the IMod shows a reduced area electrode configuration, which reduces the effects of charge injection, as well as providing a higher
10 resistance to electrical shorts.

Fig. 6 is a side view of two IMods illustrating a mechanism to alter the spring constant.

Fig. 7A shows a single material membrane tether support. Fig. 7B shows an alloyed or graded material
15 membrane tether support.

Fig. 8A shows one process for isolating the electrodes during the fabrication of a MEM structure.

Fig. 8B shows a more efficient process for isolating the electrodes during fabrication.
20

The optical impedance, the reciprocal of admittance, of an IMod can be actively modified so that it can modulate light.

One way of doing this (some aspects of which are described in United States Patent Applications Serial
25 08/238,750 filed May 5, 1994, and incorporated by reference) is by a deformable cavity whose optical properties can be altered by deformation, electrostatically or otherwise, of one or both of the cavity walls. The composition and thickness of these
30 walls, which comprise layers of dielectric, semiconductor, or metallic films, allow for a variety of modulator designs exhibiting different optical responses to applied voltages. This scheme can be considered a form of microelectromechanical structure/system (MEMS).

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Another way of actively modifying the impedance of an IMod (some aspects of which are described in United States Patent Application Serial Number 08/554,630, filed November 6, 1995, and incorporated by reference) relies
5 on an induced absorber to regulate the optical response. Such an IMod may operate in reflective mode and can be fabricated simply and on a variety of substrates.

Both the deformable and induced absorber schemes typically work in a binary mode, residing in one of two
10 states, or an analog or tunable mode, residing in one of a continuous range of states. The difference between these two modes is based primarily on the mechanical design of the IMod structure.

Some applications could use a multi-state IMod
15 that can reside in more than two states based on its mechanics and structure. A multi-state IMod can offer several advantages from both an optical performance and digital driving perspective.

Structural components in MEMS may exhibit residual
20 film stress, the tendency of a deposited film, say of aluminum, to either shrink and crack (tensile stress) or push outward and buckle (compressive stress). A variety of factors contribute to the nature and magnitude of this stress. They include parameters of the deposition
25 process as well as the temperature of the substrate during the deposition.

Control of this stress determines, in part, the forces required to actuate the structures as well as the final shapes of the structures. For example, a self-
30 supporting membrane with very high residual stress may require prohibitively high driving voltages to actuate. The same membrane also may twist or warp due to these forces.

Actuation voltage, electromechanical behavior, and
35 final shape are important characteristics of IMods. Some

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device applications exploit the electromechanical properties. Large area displays, for example, can take advantage of the inherent hysteresis of these structures in order to provide "Amemory" at the pixel location.

5 However this requires that the IMods in a given array behave in a nearly identical fashion. Since their behavior is determined by the mechanical properties of the materials, among them residual stress, the films must be deposited with great consistency over the area of the
10 display. This is not always readily attainable.

Fig. 1A is an illustration of one IMod structural design, which has been discussed in previous patent applications. This design can be described as a "double clamped" beam in that it consists of a self-supporting
15 beam 90 which is supported, or clamped, on both ends 92. When this structure is subject to residual stress, the height of the membrane (the beam) can increase or decrease depending on whether the stress is compressive or tensile respectively. In figure 1A, membrane 90 is
20 shown in a state of tensile stress, which causes the membrane to shrink in area. Because the structure is bound to the substrate at points 92, the membrane height is decreased due to this shrinkage. Conversely membrane 94, shown in compressive stress, attempts to expand with
25 the end result being a net increase or decrease in height or overall bowing of the structure.

Fig. 1B shows an improvement to this design. In this case, the movable secondary mirror 100 is connected to support posts 104 via tethers 102. The IMod is
30 fabricated on substrate 106, and incorporates stiction bumps 108. The structure has advantages with respect to residual stress. In particular, because tethers 102 are tangential to secondary mirror 100, residual stress in the material will have a tendency to be relieved by
35 causing the mirror 100 to twist in a clockwise direction

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or counter clockwise direction if the stress is compressive or tensile.

This twist is illustrated for a tensile case in Fig. 1C. Because a tensile film has a tendency to shrink, the sides of secondary mirror 100 are pulled towards the support posts 104 with which they are associated, while the mirror remains in its original plane. The twisting relieves the residual stress of the structure. This stress relief occurs after the last step of the IMod fabrication when a supporting sacrificial spacer is removed from beneath the structure. Depending on the overall design of the IMod, a certain amount of structural rotation can be tolerated. Consequently, minute variations of residual stress across the expanse of a display array are mitigated or eliminated because each IMod rotates to its individual stress relieved position, all without affecting the optical properties.

The other consequence of this relief is that stress no longer contributes, or contributes much less, to the electromechanical behavior of the device. Device characteristics such as voltage and resonant frequency are thus determined primarily by factors such as modulus of elasticity and film thickness. Both of these characteristics are more easily controlled during deposition.

Fig. 1D illustrates another geometry for a stress relieving structure relying on straight tethers 102. In this case, the mirror is rotating clockwise to relieve compressive stress. Other tether configurations, including curved or folded, are also possible,

Referring again to Fig. 1B, a micro-electromechanical structure has a tendency to stick to a surface of a substrate that it touches during operation. Structures that minimize the area of contact between movable membrane 100 and the substrate can mitigate this

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phenomenon. Stiction bumps 108 can provide this mechanism by acting as supports which contact the membrane only over a relatively small area. These structures can be fabricated using the micromachining techniques described in the previous patent applications. They can also act as bottom electrodes if suitably insulated, and exhibit certain advantages over previously described designs, which will be discussed below. In this role they may be referred to as actuation rails. These structures may also be fabricated on the movable membrane.

Referring again to Fig. 1B, damping hole 110 also enhances the performance of this structure. When the membrane is actuated i.e., pulled downward, the air between it and the substrate must be displaced. The same volume of air must be replaced when the membrane is allowed to deflect back to its quiescent position. The energy required to move this volume of air has the effect of slowing the motion of the membrane or damping its behavior. Damping is both a detriment and an advantage. Minimizing the response time of these devices is important in order to support the necessary display data rates, thus the desire exists to minimize damping. However it is also important to bring the membrane to fixed position very quickly in order to reduce the amount of light reflected, over time, which is not of the desired color. With insufficient damping, such a membrane can experience ringing, or decaying oscillation, when it is released into the undriven state. This should be minimized, and is also determined in part by damping.

One method of optimizing damping is to provide a damping hole through the body of the membrane. The hole serves to provide a supplementary path for the air during the motion of the membrane. The force required to displace and replace the air is thus lessened, and the

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effect of damping reduced. Thus choosing the size of the hole during manufacture provides a mechanism for manipulating the amount of damping the IMod experiences, and therefore its response time. Stiction bumps, 108, 5 can also assist in minimizing damping. They do so by maintaining a finite distance between the membrane and substrate so that there is a path for airflow, between the membrane and the substrate, when the membrane is fully actuated.

10 Another method for optimizing damping relies on control of the ambient gas pressure. Any IMod device, as described in previous patent applications, will be packaged in a container that provides a hermetic seal, using an inert gas. This prevents the introduction of 15 both particulate contaminants as well as water vapor, both of which can degrade the performance of the IMod over time. The pressure of this gas has a direct bearing on the amount of damping that the packaged devices will experience. Thus, the damping, and response time, may 20 also be optimized by determining the ambient gas pressure within the packaging during manufacture.

A key metric of performance in a reflective flat panel display is its brightness. Most of these displays achieve color spatially, that is each pixel is divided 25 into three sub-pixels corresponding to the colors red, blue, and green. White is achieved by maximizing the brightness of all three sub-pixels. Unfortunately, since each sub-pixel utilizes only about 1/3 of the light incident upon it, the overall brightness of the white 30 state can be low.

This can be resolved by utilizing a sub-pixel structure that is capable of directly achieving a white state, in addition to a particular color. In this fashion, the overall brightness of the display can be 35 increased because a sub-pixel in a white state utilizes a

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significantly higher fraction of the light incident upon it. The IMod design described in patent application serial number 08/554,630 is capable of reflecting either a particular color or exhibiting a "Ablack" or absorbing state. This design can be modified to include alternative states.

Figure 2A shows a perspective view of an arrangement that is capable of a black state and a white state, and illustrates the previously described tether configuration. (The double-clamped membrane of Figure 1A is also a usable mechanical design though with the mentioned sensitivities to stress.) Figure 2B shows the IMod in the two states with 204 being the undriven state, and 206 being the driven state. In the driven state the IMod absorbs incident light and appears black to a viewer looking through substrate 202. In the undriven state, the IMod appears white.

Figure 2C reveals details of the films involved. Movable membranes 208, 210, and 212, comprise three films of a metal, a dielectric, and a metal, respectively. One example could utilize aluminum of 400 nanometers (nm) thick for metal 208, silicon dioxide of 50 nm for dielectric 210, and tungsten of 14.9 nm for metal 212. Dielectric 214 could comprise a film of zirconium dioxide 54.36 nm thick, residing on substrate 26. Figure 2D illustrates the spectral reflectance function of this IMod design in the two states. Curves 216 and 218 reveal the reflectivity of the IMod in the white state and the black state, respectively

Figure 3A is a variation that is capable of three states. In this design, the thin film stack of the design in Figure 2A has been broken into separate movable membranes. Membrane 300 is a metal, 400 nm of aluminum in this case, and membrane 302 is also a metal, 14 nm of tungsten for example. Because the tungsten is so thin,

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optically neutral structural films may be required to provide the requisite mechanical integrity, which could be in the form of a supporting frame. The air gap between the two membranes functions as the dielectric.

5 Figure 3B shows a top view of this IMod revealing detail of how actuation would occur. One complication of this design is that conducting membrane 302 shields membrane 300 from the electric fields produced by the stiction/actuation bumps. Lengthening membrane 300 at

10 regions 303, 304 so that it extends beyond the footprint of membrane 302 allows membrane 300 to "Asee" the electric fields via paths 305, 307 and thus be acted upon by them.

The three possible mechanical states, and

15 associated dimensions, are illustrated in Figure 3C. Airgap dimensions 308 and 310 could be 215 nm and 135 nm. Figure 3D reveals detail of the thin films involved. Film 320 is a metal, 322 is an airgap which serves as a dielectric, 324 is also a metal, and 326 is a dielectric.

20 Figure 3E is a spectral reflectance plot of the three states. For the dimensions indicated, a black state (e.g. state 2), a blue state (state 0), and a white state (state 1) are possible, with the black, blue and white states corresponding to spectral reflectance plots, 334, 332, and 330. Fig. 3F shows plots for an IMod with green and white states 336 and 334, while Fig. 3G shows plots for an IMod with red and white states 340 and 338.

25

Like all IMods, this design exhibits electromechanical hysteresis, though it is more

30 complicated than an IMod with only two states. There is a minimum voltage which, when applied, is sufficient to keep one or both membranes in a driven or actuated state despite the mechanical forces which seek to return them to their relaxed positions.

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Fig. 4A is a representative plot showing the relationship between applied voltage and the state of the IMod. A minimum bias, V_{bias} , is required to maintain the IMod in the state into which it has been driven. State 1 and State 2 are achieved by the application of voltages V_3 and V_4 . The related hysteresis diagram is shown in Fig. 4B, with curve 400 corresponding to the electromechanical response of movable plate 302 of Fig. 3A, and curve 402 corresponding to that of movable plate 300. V_{bias} resides at the average of the centers of the two curves. Figure 4C illustrates one part of a drive circuit required to actuate such a device. Output stage 406 consists of three transistors or other suitable switches that are connected in parallel to three different voltage sources, and the two movable plates of the IMod. Driver logic 404 responds to input signals 408 in a way that allows for the selection, via the output stage, of one particular voltage to be applied to the movable membranes of IMod 410. When no voltage is applied, the IMod's membranes move to their relaxed state via mechanical forces.

Another issue that can be encountered in movable membrane structures is that of charge deposition, a phenomenon illustrated in Figs. 5A-5C. In Fig. 5A, a voltage is applied between movable plate 500 and fixed plate 504. Layer 502 is an insulating film that resides on top of fixed plate 504. If the applied voltage is sufficient to actuate the movable plate and it comes into contact with the insulator, as it does in Fig. 5B, it may deposit charge 506 on the insulator. One consequence of this is that the attractive force between plates 500 and 504 is reduced, and a higher voltage must be applied in order to achieve actuation (Fig. 5C).

This condition can be resolved by applying alternating voltages to the structure. That is, for

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every intended actuation, change the polarity of the voltage that is applied such that the deposited charge is canceled out or actually exploited. Fig. 5D illustrates the effect of applying a reverse polarity. The other
5 alternative is to eliminate the solid insulator and replace it with air. Fig. 5E illustrates the use of stiction bumps or actuation rails to accomplish this goal. Charge may still accumulate on these structures, but the area is much smaller, and therefore the
10 accumulated charge is decreased. Reverse polarity and stiction bumps may also be used together.

Electrical shorts are another concern for these devices. Referring again to Fig. 5A, the surface area of both the movable membrane (top electrode) 500 and the
15 bottom electrode 504 are equivalent. When the device is actuated (Fig. 5B), pinholes in the insulator, 502, could lead to electrical shorts and device failure. Utilizing a configuration like that shown in Fig. 5E can mitigate this issue by reducing the surface area of the surface
20 electrode so that the probability of a short producing pinhole is reduced. The surface electrode, or stiction/actuation rail, serves the aforementioned function of stiction mitigation as well. Like stiction bumps, they may be fabricated on the movable membrane
25 instead.

Another issue that complicates the fabrication of a display based on IMods is the manufacturing of a full-color display. Since different colors in an IMod are achieved by the undriven spacing of the IMod, an array
30 with three different colors will have subarrays of IMods with three different gap sizes. Consequently, there will be three different electromechanical responses for the driving electronics to contend with. The damping holes are one technique for compensating for the variation in
35 electromechanical response from color to color.

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Another technique is to vary the thickness of either the membrane, in the double clamped IMod, or the tether thickness in the tether supported IMod. The latter technique is illustrated in Fig. 6. Tether 600 on 5 IMod 602 is fabricated so that it is thinner than tether 604 on IMod 606. With the same bias voltage applied to both, IMod 602 is displaced further than IMod 606 because of its lower spring constant. Less force is required to actuate this structure and its mechanical response time 10 is lower, and it is the mechanical response time that tends to dominate. This effectively changes the overall electromechanical response of the device and thus provides a way to compensate for spacing variation. The same technique applies to the double clamped design only 15 the thickness of the entire membrane, or major parts of it, are varied. By way of example, an IMod that is red and therefore has a longer mechanical response time because of the greater undriven spacing, can be fabricated with a higher spring constant. This makes it 20 possible to match its actuation time to that of, say, the blue IMod.

In the tether supported IMod, the spring constant could be determined by lengths of the tether arms. A longer tether results in a lower spring constant and a 25 shorter tether produces a higher constant. This could be accomplished, in the same amount of total device space, by varying the position along the edge of the movable membrane to which the tether is attached. Thus, a tether connected to the center of the membrane edge would have a 30 lower (a higher) than one connected to the nearer (the farther) end, respectively.

The concept of decoupling the optical properties of the movable membrane from the structural properties was discussed in the previous patent application. The 35 fundamental idea is to fabricate a structure with

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separate elements designed and optimized to provide the required mechanical and structural characteristics and, independently, the required optical properties.

Fig. 7A reveals more detail about one possible approach. In this case the movable membrane, 700, is selected purely on the basis of its optical properties and membrane tether, 702, for its advantageous mechanical properties. Aluminum, for example, has already been shown to be useful in several IMod designs from an optical perspective, though mechanically it is subject to fatigue and stress fractures. A more suitable material might be a dielectric like aluminum oxide, silicon oxide or silicon nitride, which could be used to construct the tether.

Fig. 7B illustrates a variation on the theme where the tether is composed of either a laminated or graded material. In a laminated material, layers 706 and 710 might comprise films of aluminum oxide, providing good mechanical strength, and film 708 could be aluminum, providing electrical conductivity. For a graded material, layers 710-706 could be composed of a continuously varied material that is deposited so that at the inner surface it is pure aluminum, and at the outer surface it is pure aluminum oxide. This approach should be mechanically more robust than the laminate. Other manifestations of this technique are possible, including the use of different materials as well as alternate material variations.

The general fabrication process described in the previous patent applications relies on the concept of surface micromachining, where a sacrificial layer is deposited, a structure is formed on top of it, and the sacrificial layer is etched away. Plasma etching is one approach which has been previously described. Another etch chemistry of particular interest utilizes a gas-

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phase etchant to remove the sacrificial layer. Candidates include gases known as XeF₂, BrF₃, ClF₃, BrF₅, and IF₅. These gases have the advantageous property of etching materials such as silicon and tungsten
5 spontaneously, and without the need for a plasma to activate the etch process. Because it is a gas phase etch, as opposed to a wet etch, the sacrificial etch step is much less complicated and provides additional flexibility in the kinds of structural materials which
10 may be used. Furthermore it facilitates the fabrication of more elaborate devices with complex internal structures.

Display applications, in general, require the ability to fabricate on relatively large substrates.
15 While many finished display devices can be smaller than 1 square inch, most direct view displays start at several square inches and can be as large as several hundred square inches or larger. Additionally, these displays utilize glass or plastic substrates that are not found in
20 traditional semiconductor manufacturing plants. MEMS, which are primarily both silicon based and fabricated on silicon substrates, have been historically fabricated in semiconductor type facilities. However the need to fabricate large arrays of MEM devices on large
25 substrates, a need which is exemplified by an IMod based display, cannot be served using traditional semiconductor manufacturing practices or facilities.

Alternatively, there exists a large and growing base of facilities that could also be applied to the
30 manufacture of large arrays of IMods and other MEMS. This manufacturing base comprises facilities and factories that are currently used to manufacture Active Matrix LCDs. The book "ALiquid Crystal Flat Panel Displays", by William C. O'Mara, is incorporated herein
35 by reference. These facilities are appropriate because

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the bulk of the fabrication process is related to the active matrix component, i.e. the thin film transistor (TFT) array that drives the LCD.

While there exist a variety of TFT fabrication processes, they all share several components which make them amenable to the fabrication of large area surface micromachined MEMS. First, the substrate of choice is glass or plastic, which is readily available in large sized formats. Impurities in these materials may be isolated chemically from the fabricated structures by depositing an organic or inorganic film, such as a metallic oxide, on the surface of the substrate prior to fabrication. In addition, key materials deposited include silicon, tungsten, molybdenum, germanium, and tantalum, all of which are suitable sacrificial materials for gas phase etchants, as well as tantalum pentoxide, silicon dioxide, silicon nitride, and aluminum, which are suitable optical, insulating, structural, optical, and conducting materials. In general, all photolithography, process tooling, and testing are oriented towards large arrays and large area devices. Finally, the process for fabricating the TFTs can be utilized to fabricate electronics in conjunction with the MEM devices in order to provide driver circuitry and intelligent logic functions. Thus in conjunction with the gas phase etch, Active Matrix LCD fabs and their associated processes provide a readily usable manufacturing vehicle for IMod based displays in particular, and large area (at least as large of 8" x 8" or 8" in diameter) MEM devices in general.

Two general approaches for fabricating TFTs and IMods or other MEM devices can be described as decoupled and overlapping. In the former the requisite TFT based circuitry is fabricated first, and then the IMods are fabricated subsequently. A more efficient approach is to

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fabricate the TFT array and the IMod array in a way that allows the sharing or overlapping of steps in each process. A representative TFT process sequence is shown in the following:

- 5 1. Deposit gate metal (molybdenum or tantalum for example).
2. Pattern gate metal.
3. Deposit insulator and amorphous silicon.
4. Pattern insulator and silicon.
- 10 5. Deposit display electrode (aluminum for example).
6. Pattern display electrode.
7. Deposit source/drain/signal line metal (aluminum).
- 15 8. Pattern source/drain/signal line.
9. Pattern silicon.
10. Deposit passivation film.

A representative IMod process sequence is shown in the following:

- 20 1. Deposit dielectric/primary mirror (molybdenum or tantalum for primary mirror).
2. Pattern primary mirror.
3. Deposit insulator and amorphous silicon.
4. Pattern insulator and silicon.
- 25 5. Deposit secondary mirror (aluminum).
6. Pattern secondary mirror.
7. Etch sacrificial material (silicon).

Comparison of these two process sequences reveals that steps 1-6 are functional equivalents on a
30 fundamental level and, obviously, located at the same place in their respective sequences. This similarity benefits both the decoupled and overlapping processes in

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several ways. First, similarity in materials minimizes the total number of dedicated deposition tools required, as well as the number of etchant chemistries. Second, identical location of equivalent steps streamlines the overall process flow. Finally, for an overlapping process, some of the steps can be shared. The consequence of this is an overall reduction in the total number of process steps required to fabricate both the IMod array and the TFT circuitry, reducing both complexity and cost. In general the process and facilities for manufacturing the active matrix component of the AMLCD would appear to be ideally suited for IMod fabrication.

The surface micromachining of structures can be simplified by using a process which is illustrated in Figs. 8A and 8B. Fig. 8A illustrates one technique for fabricating an isolated primary electrode. In step 1, the primary electrode, 800, has been patterned, by virtue of mask 802, and etched on substrate 804. In step 2, a blanket insulating layer, 806, has been deposited along with the sacrificial material, 808, and mask 810. Finally in step 3, the sacrificial layer has been patterned and etched and secondary electrode 812 has been deposited over it. It can be seen that insulating layer 806 provides electrical isolation between the secondary electrode, 812, and the primary electrode, 800. This process requires the use of two masking steps which form masks 802 and 810.

Fig. 8B reveals a simplified sequence. Step 1 shows primary electrode, 800, insulator, 806, and sacrificial layer, 808, deposited in a blanket fashion with mask layer, 802, in place. In step 2, layers 800, 806, and 808 have been etched and the mask, 802, has been stripped away having served its purpose. This etch differs however in that the insulating layer, 806, has

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been underetched by virtue of overetching the primary electrode, 800. This produces an insulating ledge. Such a ledge can be achieved by properly selecting the materials and etchants involved. For example, if
5 sacrificial layer, 808, is made of silicon, insulating layer 806 made from silicon dioxide, and primary electrode 800 made from tungsten, the tungsten layer may be overetched using a solution of hydrogen peroxide and water without having any effect on the silicon or silicon
10 dioxide. The secondary electrode, 812, is then deposited in a blanket fashion in step 3. Insulating layer, 806, still provides isolation between the primary and secondary electrodes, 800 and 812 respectively, because the insulating ledge prevents primary electrode, 800,
15 from making contact with secondary electrode, 812, during the deposition of the secondary electrode. The overall result is a reduction, by one, of the number of mask steps required to form an insulating barrier between the two electrodes. This occurs because the single mask
20 layer provides the pattern for the multiple etchants used to define the three layers.

Other embodiments are within the scope of the following claims.

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What is claimed is:

1. An interferometric modulator comprising a cavity defined by two walls, at least two arms connecting the two walls to permit motion of the walls relative to each other, the two arms being configured and attached to a first one of the walls in a manner that enables mechanical stress in the first wall to be relieved by motion of the first wall essentially within the plane of the first wall.
2. The modulator of claim 1 in which the motion of the first wall is rotational.
3. The modulator of claim 1 in which each of the arms has two ends, one of the ends attached to the first wall and a second end that is attached at a point that is fixed relative to a second one of the walls, the point of attachment of the second end being offset, with reference to an axis that is perpendicular to the first wall, from the end that is attached to the second wall.
4. The modulator of claim 1 in which the arms are configured to achieve a desired spring constant.
5. The modulator of claim 4 in which the lengths of the arms are configured to achieve the desired spring constant.
6. The modulator of claim 4 in which the thicknesses of the arms are configured to achieve the desired spring constant.
7. The modulator of claim 4 in which the positions along edges of the first wall where the arms are attached is selected to achieve the desired spring constant.
8. The modulator of claim 1 in which the first wall has two essentially straight edges and one end of each of the arms is attached at the middle of one of the edges.

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9. The modulator of claim 1 in which the first wall has two essentially straight edges and an end of each of the arms is attached at the end of one of the edges.

5 10. The modulator of claim 9 comprising a third arm connecting the two walls.

11. The modulator of claim 1 comprising a third arm and a fourth arm each connecting the two walls.

10 12. The modulator of claim 10 or 11 in which the arms define a pinwheel configuration.

13. An array of interferometric modulators, each of the interferometric modulators comprising a cavity defined by two walls, at least two arms connecting the two walls to permit motion of the walls relative to each other, the walls and arms of different ones of the modulators being configured to achieve different spring constants associated with motion of the walls relative to each other.

15 14. The modulator of claim 13 in which each of the arms has two ends, one of the ends attached to the first wall and a second end that is attached at a point that is fixed relative to a second one of the walls, the point of attachment of the second end being offset, with reference to an axis that is perpendicular to the first wall, from the end that is attached to the second wall.

20 15. A method of fabricating an interferometric modulator comprising forming two walls of a cavity connected by at least two arms and, after the forming, permitting the a first one of the walls to rotate in the plane of the first wall relative to the arms to relieve mechanical stress in the first wall.

25 30

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16. An interferometric modulator comprising three walls that are generally parallel to one another, the walls being supported for movement of at least one of the walls relative to the other two, and control circuitry
5 for driving at least one of the walls to discrete positions representing three discrete states of operation of the modulator.

17. The modulator of claim 16 in which in one of the three discrete states, there is a gap between the
10 first and a second of the two walls and a gap between the second and a third of the two walls, in a second of the three discrete states, there is a gap between the first and the second of the two walls and no gap between the second and the third of the two walls, and in the third
15 of the three discrete states, there is no gap between the first and the second of the two walls and no gap between the second and the third of the two walls.

18. The modulator of claim 16 in which each membrane comprises a combination of dielectric, metallic,
20 or semiconducting films.

19. An interference modulator comprising a cavity defined by two walls that are movable relative to one another to and from a contact position in which the two walls are essentially adjacent to one another, and
25 spacers mounted to form part of one of the walls to reduce the surface area over which the two walls touch in the contact position.

20. The modulator of claim 19 in which the spacers comprise electrodes and further comprising
30 conductors to feed current to the electrodes.

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21. An interference modulator comprising a cavity defined by two walls that are separated by a fluid-filled gap, the two walls being movable relative to each other to change the volume of the gap, and an aperture in one
5 of the walls configured to control the damping effect of fluid moving into or out of the gap as the volume of the gap changes.

22. The modulator of claim 15 in which the aperture comprises a round hole in the center of the
10 wall.

23. An interference modulator comprising at least two walls that are movable relative to each other to define a cavity between them, the relative positions of the walls defining two modes, one in which the modulator
15 reflects incident light and appears white and another in which the modulator absorbs incident light and appears black.

24. The modulator of claim 23 in which one of the walls comprises a sandwich of a dielectric between
20 metals, and the other of the walls comprises a dielectric.

25. An interferometric modulator comprising a cavity defined by two walls, at least two arms connecting the two walls to permit motion of the walls relative to
25 each other, with the response time of the modulator being controlled to a predetermined value by a combination of at least two of: the lengths of the arms, the locations at which the arms are connected to the walls, the thickness of one of the walls, the thickness of the arms,
30 the presence and dimensions of damping holes, and the ambient gas pressure in the vicinity of the modulator.

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26. An interferometric modulator comprising a cavity defined by two walls, at least two arms connecting the two walls to permit motion of the walls relative to each and a charge deposition mitigating device comprising
5 at least one of actuation rails or the application of alternating polarity drive voltages.

27. An interferometric modulator comprising one or more cavities each defined by at least two walls held by a support, at least one of the walls or the support
10 comprising at least two materials such that the electrical, mechanical, or optical properties of the wall or the support differ at different locations in a cross-section of the wall or the support.

28. The modulator of claim 27 in which at least
15 one of the walls comprises a laminate of two or more discrete materials.

29. The modulator of claim 27 in which at least one of the walls comprises a gradient of two or more materials.

20 30. The modulator of claim 27 in which the support comprises a laminate of two or more discrete materials.

31. The modulator of claim 27 in which the support comprises or a gradient of two or more materials.

25 32. The modulator of claim 27 in which the two materials exhibit respectively different and complementary electrical, mechanical, or optical properties.

33. A method for use in fabricating a
30 microelectromechanical structure, comprising using a gas phase etchant to remove a deposited sacrificial layer.

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34. The method of claim 33 in which the substrate upon which the microelectromechanical structure is fabricated is substantially immune to the effects of the gas phase etchant.

5 35. The method of claim 33 in which the substrate is chemically isolated from the microelectromechanical structures by virtue of an inert film coating.

36. The method of claim 33 in which the MEMS comprises an interference modulator in which a wall of
10 the modulator is formed on the substrate and a plasma, a liquid, or a gas phase etchant removes the sacrificial layer from between the wall and the substrate.

37. The process of claim 36 in which the gas phase etchant includes one of the following: XeF₂, BrF₃,
15 ClF₃, BrF₅, or IF₅.

38. The process of claim 33 in which the sacrificial layer used includes silicon, molybdenum, and tungsten, tantalum or germanium.

39. A method of making arrays of
20 microelectromechanical structure on a production line comprising

micromachining electromechanical structures on a surface of a glass or plastic substrate that is at least as large as 8" x 8" or 8" in diameter.

25 40. The method of claim 39 in which electronic features are fabricated in conjunction with the MEMS.

41. The method of claim 39 in which the microelectromechanical structure comprises interference modulators.

30 42. The method of claim 39 in which steps of forming the electronic features are overlapping with steps of micromachining the structures.

43. The method of claim 39 in which steps of forming the electronic features are non-overlapping with
35 steps of micromachining the structures.

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44. A method of making a MEM structure in which the sacrificial layer and the primary actuating electrode are patterned and etched in a single masking step.

45. A method for making a MEM structure in which
5 the primary actuating electrode and the secondary actuating electrode are isolated by virtue of underetching the insulating layer.

46. A method of making a surface micromachined MEM structure in which the sacrificial layer is patterned
10 and etched in one step, and the insulating layer and primary actuation electrode are patterned and etched in a separate step.

47. A method of making a surface micromachined MEM structure in which the sacrificial layer, the
15 insulating layer, and the primary actuating electrode are patterned and etched in a single masking step.

48. A method of making a MEM structure in which the primary actuating electrode and the secondary actuating electrode are electrically isolated by virtue
20 of underetching the insulating layer.

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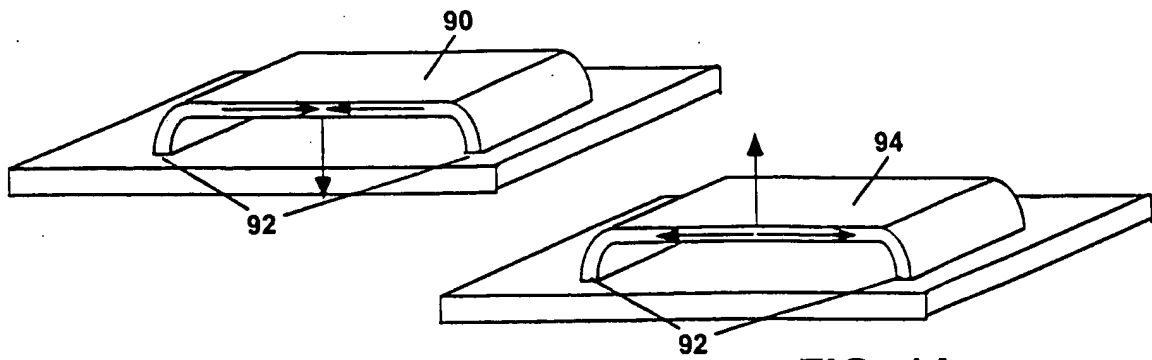


FIG. 1A

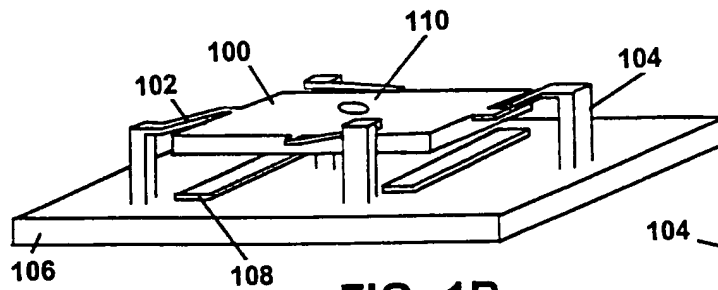


FIG. 1B

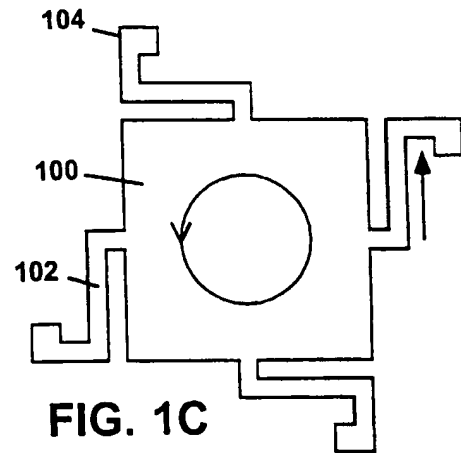


FIG. 1C

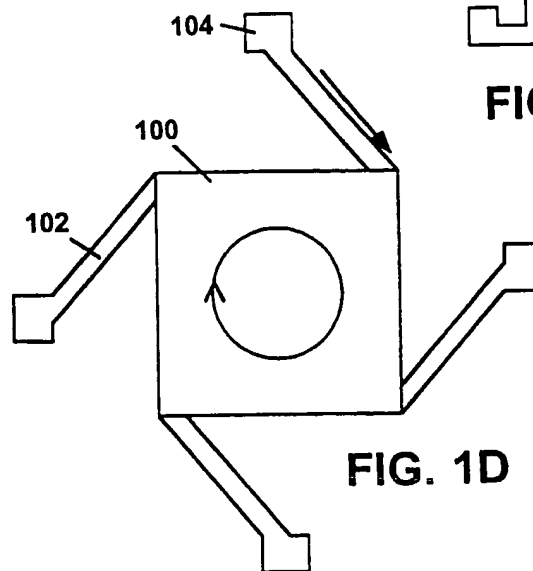


FIG. 1D

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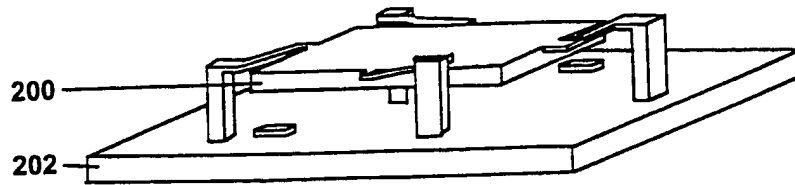


FIG. 2A

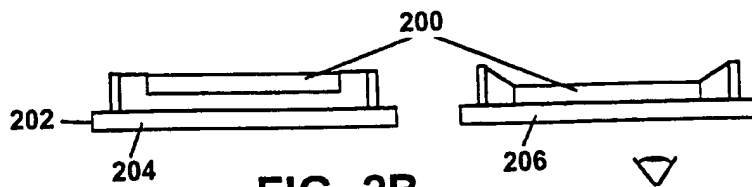


FIG. 2B

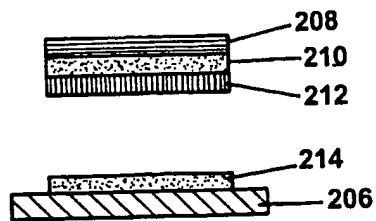


FIG. 2C

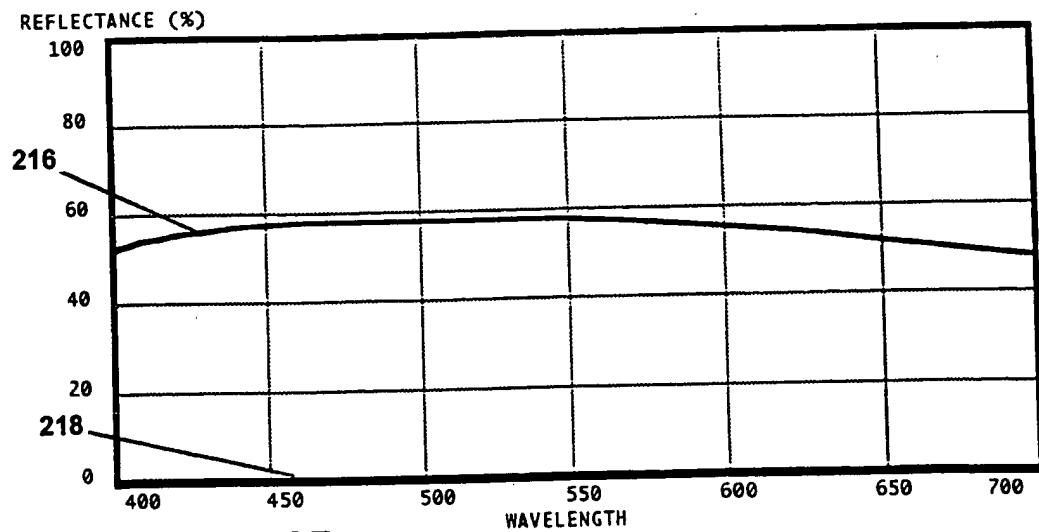


FIG. 2D

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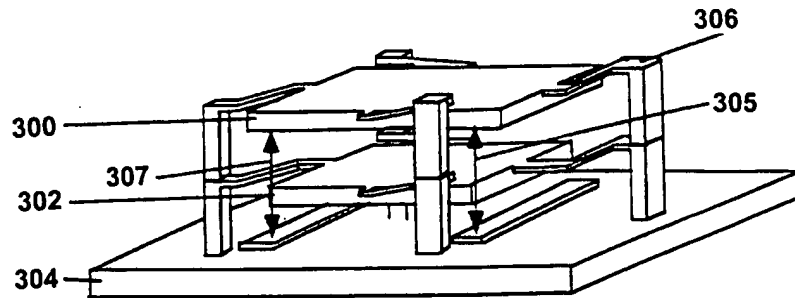


FIG. 3A

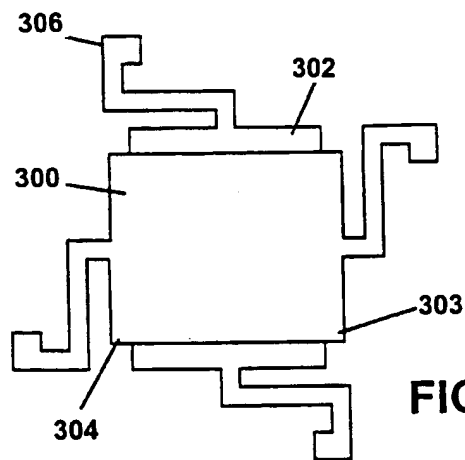


FIG. 3B

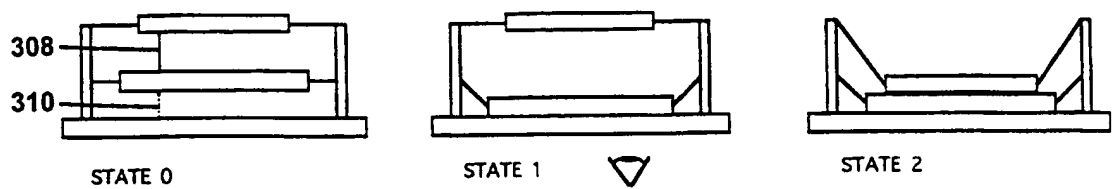


FIG. 3C

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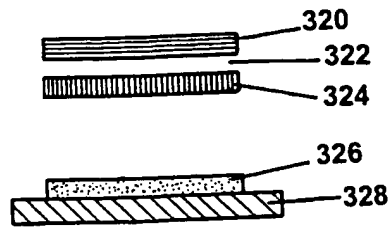


FIG. 3D

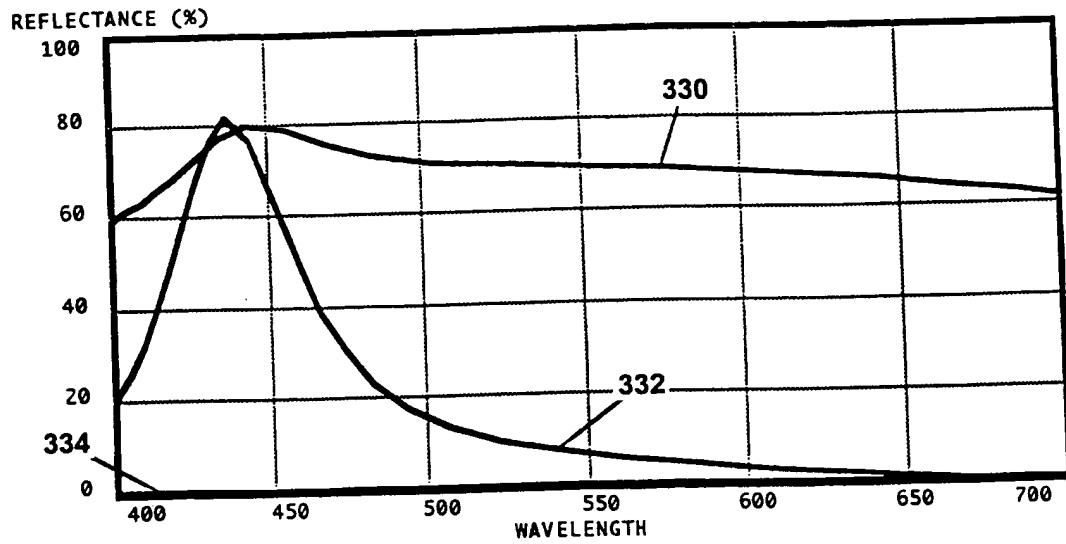


FIG. 3E

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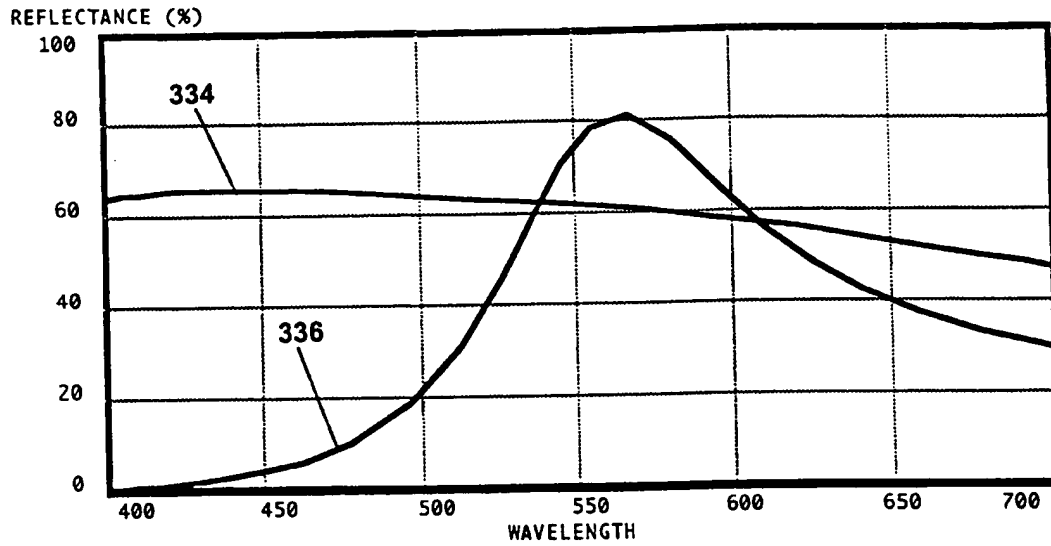


FIG. 3F

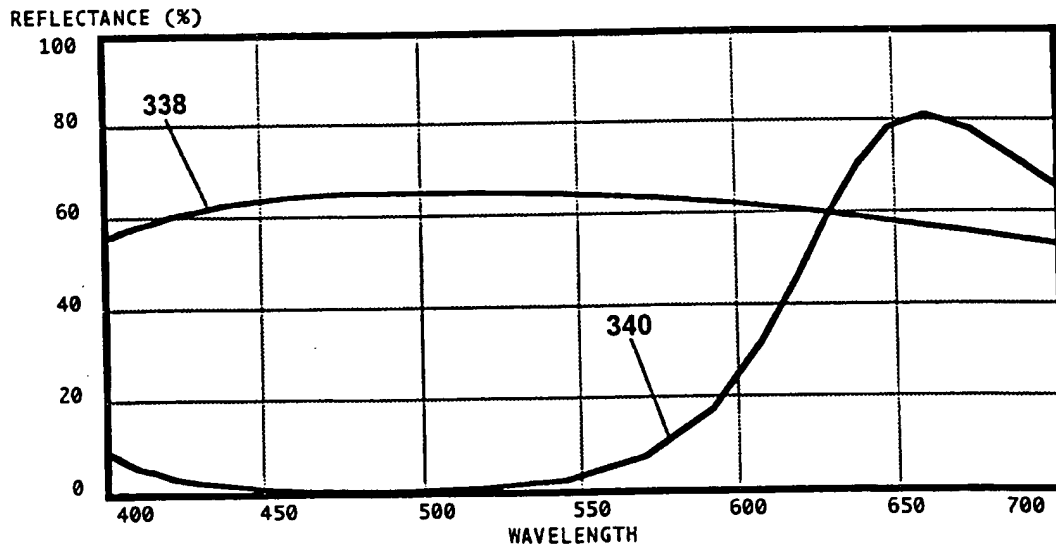


FIG. 3G

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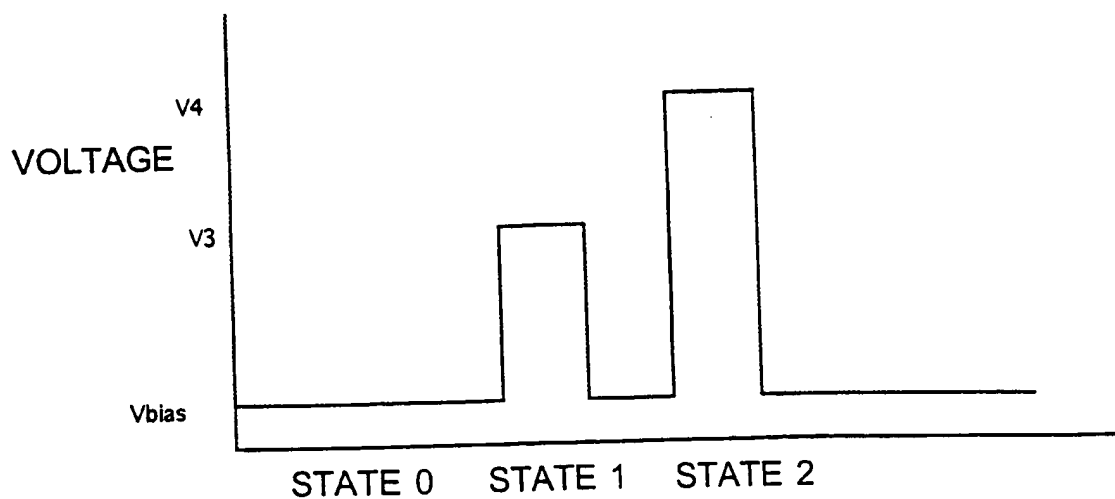


FIG. 4A

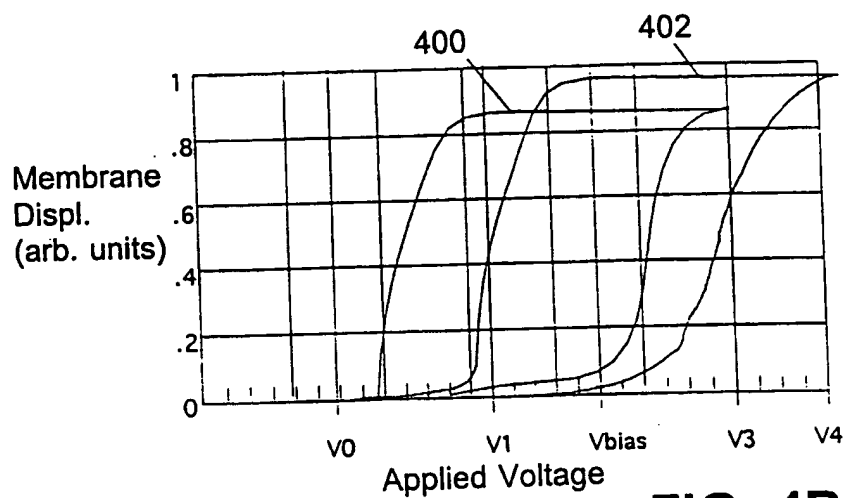


FIG. 4B

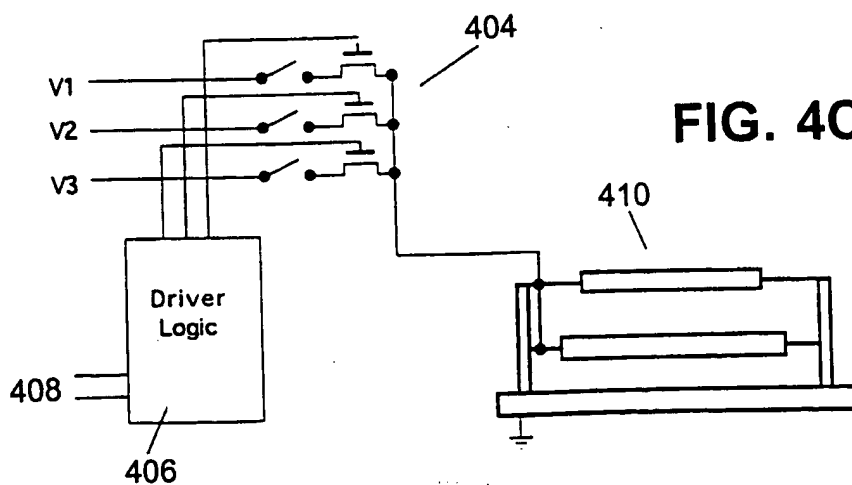
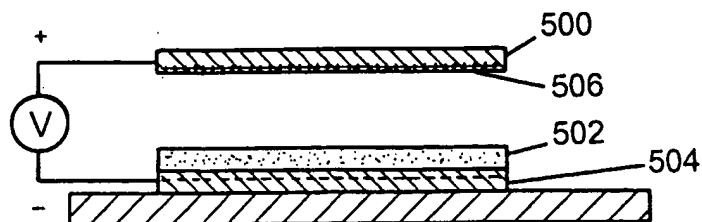
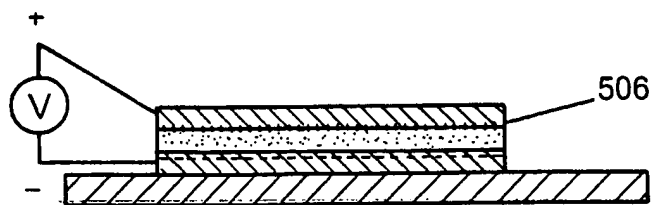
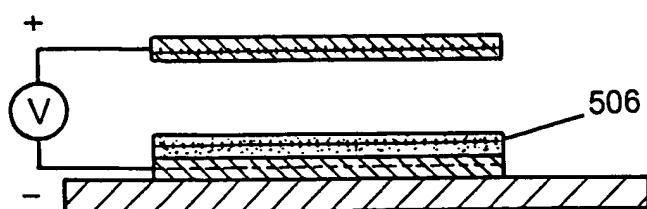
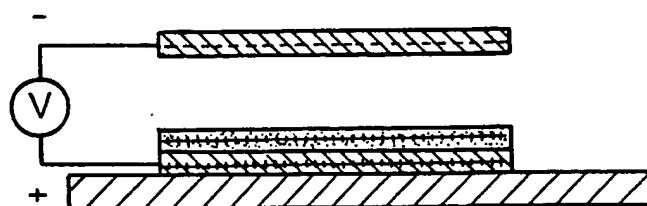
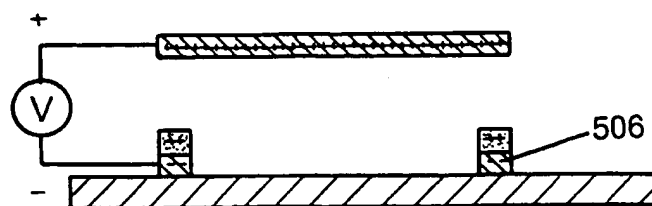


FIG. 4C

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**FIG. 5A****FIG. 5B****FIG. 5C****FIG. 5D****FIG. 5E**

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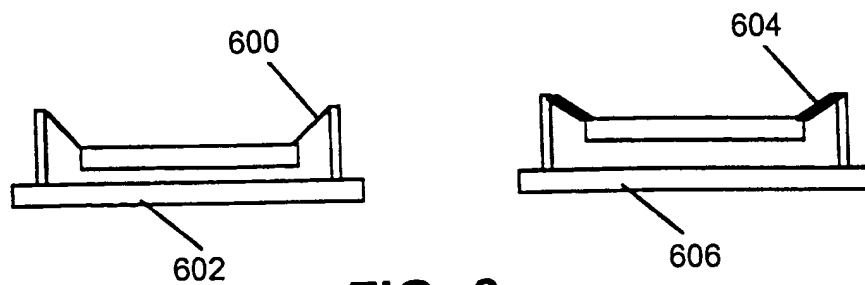


FIG. 6

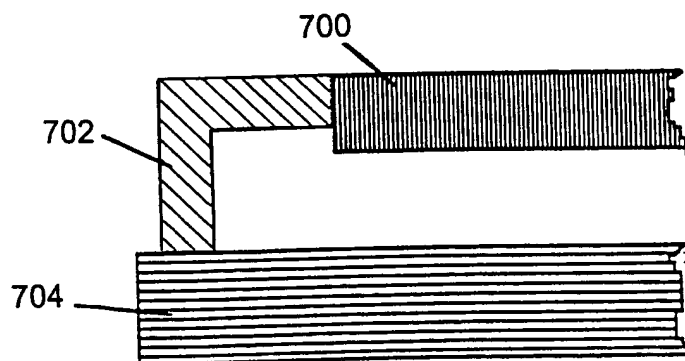


FIG. 7A

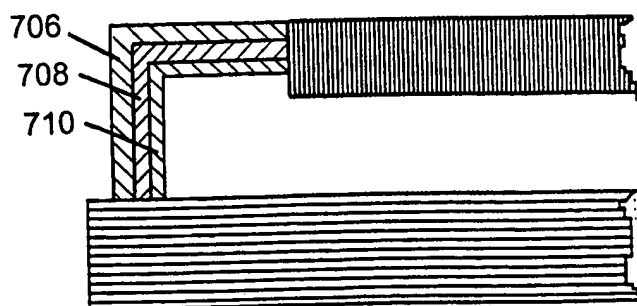


FIG. 7B

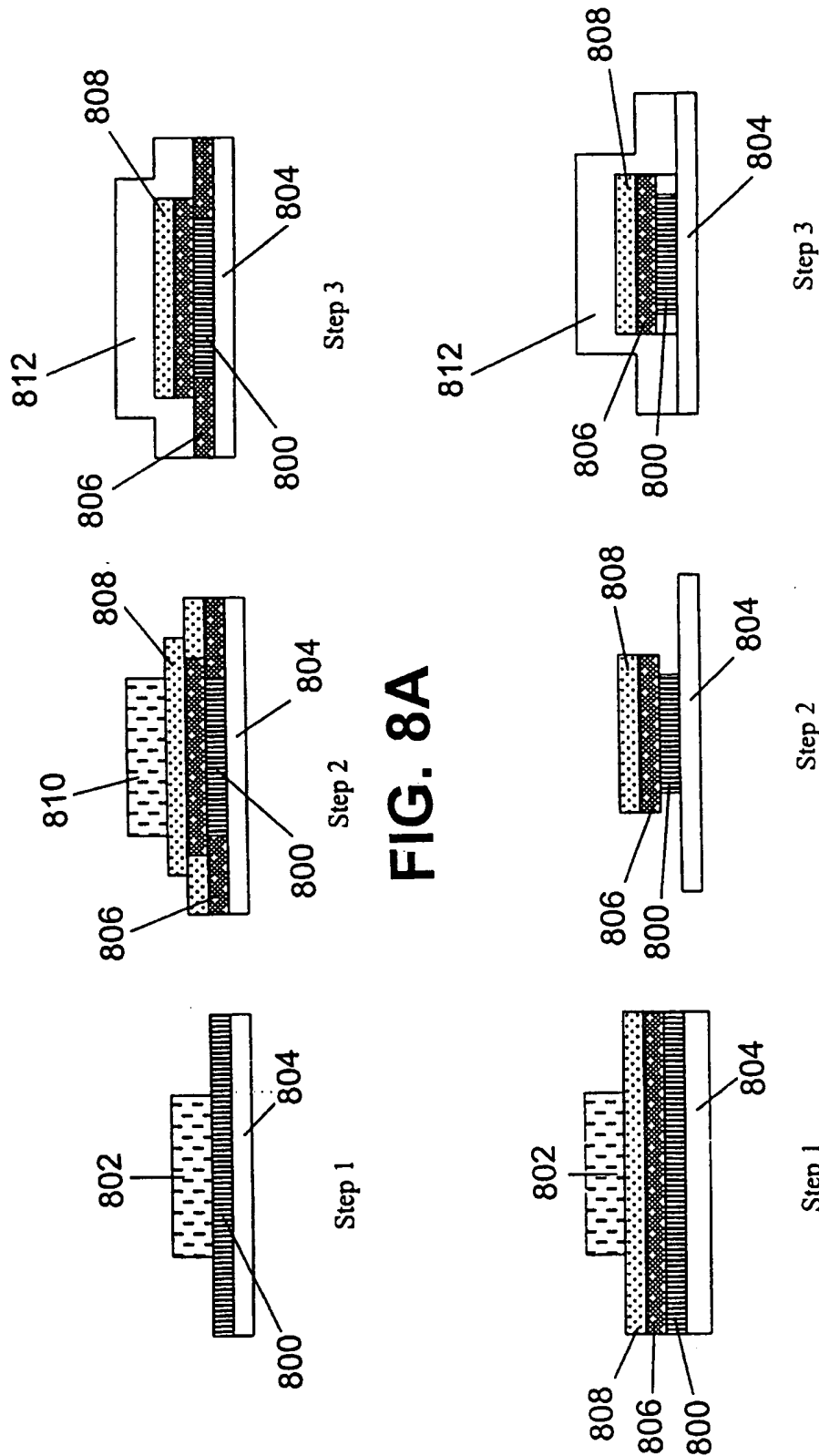


FIG. 8A

FIG. 8B

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